Stress appraisal in periodontium of maxillary first molar using various intrusive forces: A finite element analysis study

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ABSTRACT

Introduction: Maxillary molar intrusion has been regarded as one of the difficult orthodontic tooth movements when prevention of undesirable movement and root resorption are empirically considered. The purpose of the study was to evaluate the effects of various intrusive forces on maxillary first molar using - finite element method. **Materials and Methods:** Geometric model of maxillary 1st molar was generated using software ANSYS Workbench 11. The loading condition was designed to mimic conventional orthodontic tooth movement which was subjected to three different intrusive force magnitudes via 150 g, 180 g and 210 g and was put through finite element analysis (FEA). **Results:** The results were suggested high stress concentration at furcation level of the tooth and compression was seen in apical third of root area of the periodontal ligament (PDL) except in palatal side of palatal root. **Conclusion:** The furcation area of the tooth is most prone to root resorption and compression was observed in apical third of all root area of PDL except in palatal side of palatal. Displacement at cervical region in palatal side of PDL, at central fossa of the tooth and at the cervico-palatal region of alveolar bone. The results gained through FEA should be integrated with the clinical experiences to maximize accuracy.

Key words: Displacement, finite element analysis, furcation, molar intrusion, periodontal ligament

Introduction

Orthodontic tooth movement is a complex procedure that occurs as a sequel to various biomechanical changes in periodontium. Magnitude and direction of forces should be considered to prevent undesirable movement and root resorption.[1,2] Supra-eruption of maxillary molars usually results from early loss of antagonistic teeth. The elongated dentoalveolar process may induce problems such as functional disturbances and occlusal interferences and cause great difficulty during prosthetic reconstruction. Conventional options include coronal reduction of molar crown-which requires root canal therapy - and crown restorations or posterior subapical osteotomy with risk of general anesthesia and high cost.[3]

Surgical miniplates[4] and miniscrews[5,6] is now growing in popularity because of its ability to provide absolute anchorage. A study by Kuroda et al.[7] used titanium screw anchorage treat open bites and stated that their results were similar to those obtained by two-jaw orthognathic surgery.

Studies about biomechanical effects such as stress, strain and displacements on teeth and the surrounding tissues are limited.[8] In-vivo studies are not sufficient in assessing biomechanical effects such as stress and strain, finite element analysis (FEA), a valuable option for evaluation of biomechanical factors in orthodontics. The finite element method (FEM) is a highly precise technique used to analyze structural stress. Used in engineering for years, this method uses the computer to solve large equations to calculate stress on the basis of physical properties of the structure being analyzed.

FEA is a numeric method with which stress, strain and deformation of structures with complex geometries can be studied in various loading and boundary conditions. Its philosophy is based on dividing complicated structures into

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manageable pieces called elements. FEM has the ability to include heterogeneity of tooth material and irregularity of tooth contour in the model design and relative ease with which loads can be applied at different directions and magnitudes for a more complete analysis.

The purpose of this study was to elucidate stress and displacement in the periodontal ligament (PDL), tooth and alveolar bone by applying three different intrusive force - 150 g, 180 g and 210 g - using FEMs.

Materials and Methods

A geometric model was constructed using ideal tooth dimensions of the maxillary molar.[9] Dimensions of tooth were as follows, crown length 7.5 mm, mesio-distal width at cervix 8 mm and labiolingual width 10 mm, root length of buccal roots 12 mm (mesio buccal and disto buccal) and palatal root 13 mm [Figure 1]. Construct PDL of 0.25 mm around it with cancellous bone and hard bone of 1.4 mm each boundaries around it [Figure 2].

This geometric model was converted into finite element model. The finite element modeling is representative of
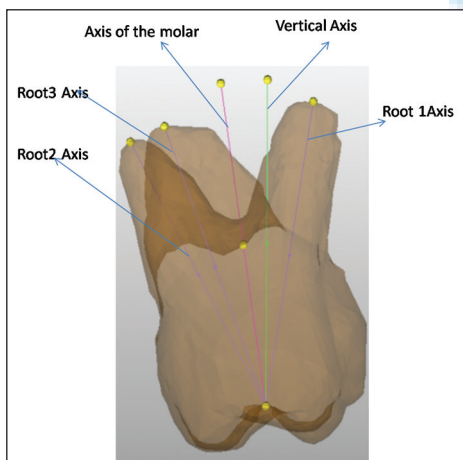
geometry in terms of a finite number of elements and nodes. This process is called as discretization. The main idea behind discretization is to improve the accuracy of results. Finite element model was created using hypermesh software using three-dimensional-4 noded tetrahedral elements [Figures 3 and 4]. The software used for geometric modeling was ANSYS Workbench 11 (403 MSX Tower 2, Alpha 1, Greater Noida).

Total nodes = 8149; Total elements = 35242.

The different structures involved in this study include teeth, the PDL and alveolar bone. The material properties used are derived by McGuinness *et al*.[10] and were also used in finite element studies done by Tanne *et al*.[11] These materials properties were the average values as listed in Table 1.

The nodes attached to the area of the outer surface of bone were fixed in all directions to avoid free body movement of a tooth.
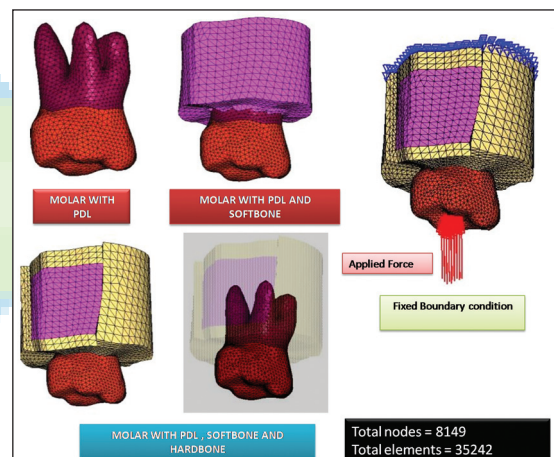

Figure 2: Three-dimensional finite element model of maxillary first molar along with PDL and alveolar bone

Figure 1: Geometric model of the tooth under consideration

Figure 3: Three-dimensional model of maxillary molar using mimic software
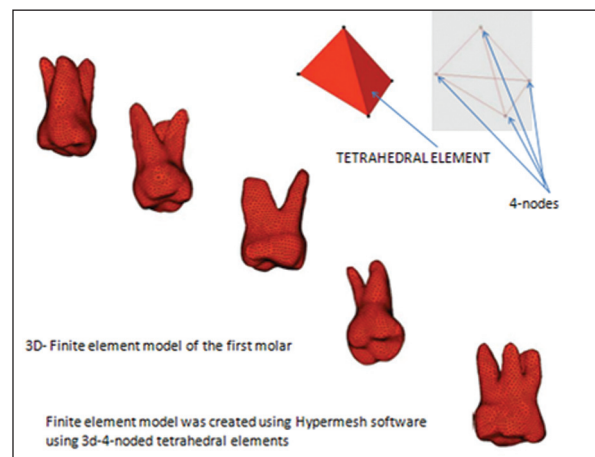

Figure 4: Three-dimensional finite element model of maxillary first molar

The loading condition was designed to mimic conventional orthodontic tooth movement. Three different types of loads were used to bring about intrusion 150 g, 180 g and 210 g force. By using FEM, the initial vertical displacement and von-mises stress distribution were calculated.

Results

Various contours through the displacement contours, maximum principal stress and von-mises stress generated were calculated for PDL, tooth and alveolar bone respectively when intrusive forces of 150 g, 180 g and 210 g are applies on the maxillary first molar [Figures 5-13].

Displacement Contour

The displacement was seen in all three axes but the maximum displacements in the periodontium have been depicted in figures. In PDL, as force was applied in the vertical direction, it resolved in three directions: x, y and z axes respectively. The amount of maximum displacement varied from 1.4×10^{-3} to 2×10^{-3} mm at cervical region at the mesial side of PDL when force was applied in x-axis or buccolingual direction and increased from 150 g to 180 g to 210 g. Amount of displacement varied from 0.5×10^{-3} to 0.75×10^{-3} mm at apical region of palatal root of PDL when force was applied in y-axis or mesiodistal direction and increased from 150 g to 180 g to 210 g. Amount of

displacement varied from 4.2×10^{-3} to 5.9×10^{-3} mm at cervical region in palatal side of PDL when force was applied in z-axis or axial/vertical direction and increased from 150 g to 180 g to 210 g [Figure 5a-c].

On the application of force in the vertical direction, tooth is displaced in three directions - x, y and z axis respectively. Displacement was not equal in all cusp of tooth as tooth was inclined mesiolingually, was not at the same level from occlusal surface maximum displacement varied from 3.5×10^{-3} to 4.9×10^{-3} mm at buccal cusp tip when force was applied in x-axis or buccolingual direction and increased from 150 g to 180 g to 210 g. Maximum displacement varied from 0.5×10^{-3} to 0.8×10^{-3} mm at mesiobuccal cusp tip when force was applied in y-axis or mesiodistal direction and increased from 150 g to 180 g to 210 g. Maximum displacement varied from 6.4×10^{-3} to 9×10^{-3} mm at central fossa when force was applied in z-axis or axial/vertical direction and increased from 150 g to 180 g to 210 g [Figure 6a-c].

On loading with three intrusive forces displacement of the tooth was seen mesiobuccal vertically.

In alveolar bone as we apply force in the vertical direction, in alveolar bone it resolved in 3 directions - x, y and z axis respectively. Amount of maximum displacement varied from 1.3×10^{-3} to 1.8×10^{-3} mm at cervical region of mesiopalatal area of alveolar bone when force was applied in x-axis or buccolingual direction and increased from 150 g to 180 g to 210 g. Amount of maximum displacement varied from 0.89×10^{-3} to 1.25×10^{-3} mm at palatal region of alveolar bone when force was applied in y-axis or mesiodistal direction and increased from 150 g to 180 g to 210 g. Amount of maximum displacement varied from 4×10^{-3} to 5.6×10^{-3} mm at cervicopalatalregion of

Table 1: Mechanical properties

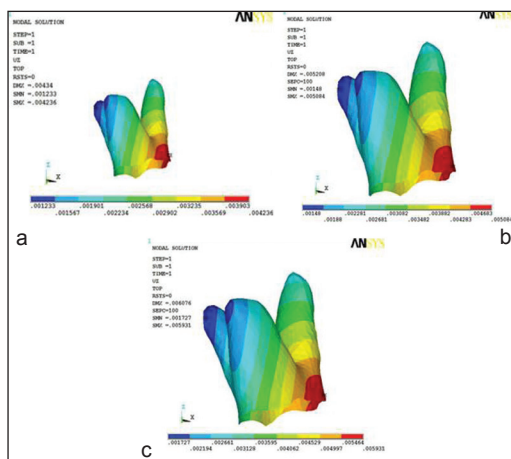|	Young's modulus (MPa)	Poisson's ratio
Alveolar bone	1370	0.3
Cortical bone	13700	0.26
Periodontal membrane	0.6668	0.49
Teeth	19613.3	0.15

Figure 5: Displacement of periodontal ligament in Z-axis (a) at 150 g force (b) at 180 g force (c) at 210 g
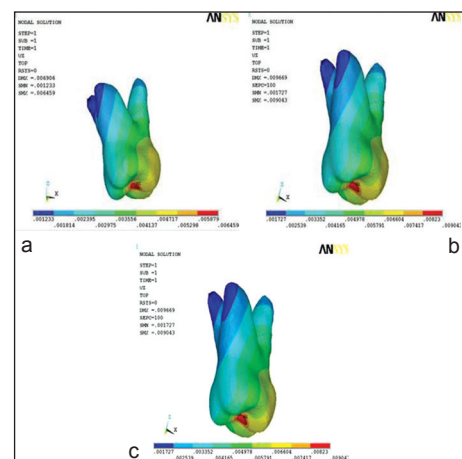

Figure 6: Displacement in tooth in Z-axis (a) at 150 g force (b) at 180 g force (c) at 210 g

alveolar bone when force was applied in z-axis or axial/vertical direction and increased from 150 g to 180 g to 210 g [Figure 7a-c].

On loading with 3 intrusive forces displacement of alveolar bone was seen in the cervical region of the mesio-palatal region of alveolar bone.

Maximum Principal Atress Contours

As force was applied in the vertical direction, compression was seen in whole of the PDL except in the area of trifurcation where stretching was seen as a result of tensile forces. Maximum principal stress increased from 0.17×10^{-3} to 0.24×10^{-3} MPa in trifurcation area of PDL when forces were increased from 150 g to 180 g to 210 g of force [Figure 8a-c].

At the tooth level, as forces were applied in the vertical direction, compression occurred only in the area of central fossa. Maximum principal stress increased from 7.48 to 10.48×10^{-3} MPa when forces were increased from 150 g to 180 g to 210 g of force [Figure 9a-c].

In alveolar bone, in the vertical direction, there was compression in the apical area of bone covering palatal root. Maximum principal stress increased from 0.61 to 0.793×10^{-3} MPa when forces were increased from 150 g to 180 g to 210 g of force [Figure 10a-c].

Von-Mises Stress Contours

In PDL, with force application in the vertical direction, compression was seen in apical third of all root area of PDL except in palatal side of palatal root of PDL area where stretching was seen (tensile forces were generated). Von-mises stress increased from 0.19×10^{-3} to 0.27×10^{-3} Mpa in trifurcation area of PDL when forces were increased from 150 g to 180 g to 210 g of force [Figure 12a-c]. Application of force in the vertical direction, lead to
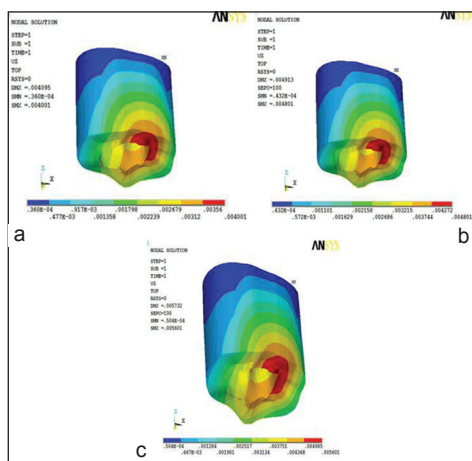

Figure 7: Displacement of alveolar bone in Z-axis (a) at 150 g force (b) at 180 g (c) at 210 g
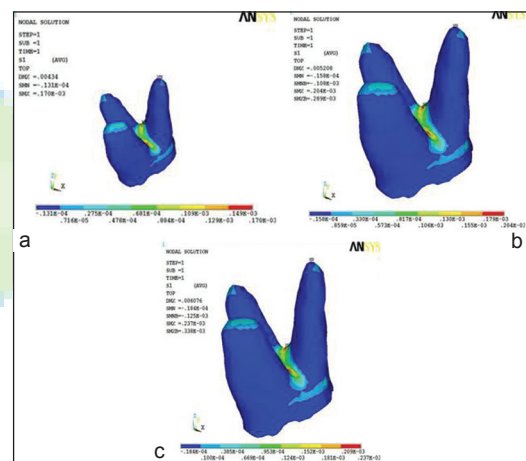

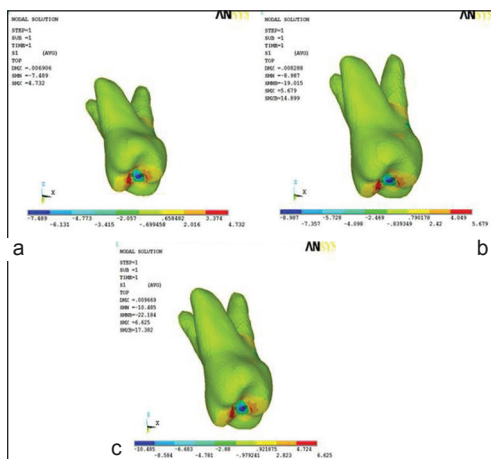**Figure 8:** Maximum principal stress contours in periodontal ligament (a) at 150 g (b)180 g and (c) 210 g

Figure 9: Maximum principal stress contours in tooth (a) at 150 g (b) at 180 g (c) at 210 g
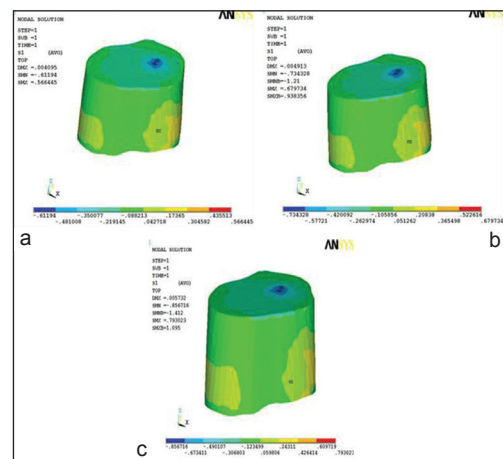

Figure 10: Maximum principal stress in alveolar bone (a) at 150 g (b) at 180 g and (c) at 210 g

compression, in all areas of tooth except in central fossa region where tensile forces were generated. Von-mises stress increased from 15.64 to 21.9 $\times$ 10^{-3} Mpa in central fossa area of tooth when forces were increased from 150 g to 180 g to 210 g of force [Figure 12a-c].

In alveolar bone compression was seen in all except in the apical region of alveolar bone covering palatal root where tensile forces were seen where von-mises stress increased from 1.46 to 2.045 $\times$ 10^{-3} Mpa when forces are increased from 150 g to 180 g to 210 g of force [Figure 13a-c].

Discussion

In the present study, the FEM provided a mathematical model that allowed quantification of displacement and stress patterns in periodontium of maxillary first molar by incorporation of PDL, tooth and alveolar bone. Displacement pattern was seen in all 3-axes (x, y and z) on application of three different intrusive forces.

To avoid root resorption, optimal force(s) have been advocated. Park *et al.*[12] used 150-250 g, Jeon *et al.*[13] used 400 g, Erverdi *et al.* used 200 g, Xun used 150 g. In the present study, 3 force values, i.e., 150 g, 180 g and 210 g were used to calculate stress and displacement generated in the periodontium.

Results showed the displacement of tooth at mesiobuccal area in a vertical direction while displacement was seen in cervico mesio-palatal area of the PDL; the displacement in alveolar bone was seen in the cervical region mesio-palatally. Amount of intrusion seen was 6.4 $\times$ 10^{-3} mm for 150 g, 7.7 $\times$ 10^{-3} mm for 180 g and 9 $\times$ 10^{-3} mm for 210 g of forces applied [Graph 1a-c].

The stress patterns in PDL, tooth and alveolar bone have been displayed by separate illustrations, so that the complex responses of these tissues to different loads could be readily compared. Von-mises stress patterns showed that in PDL, compression took place at the apical third of the
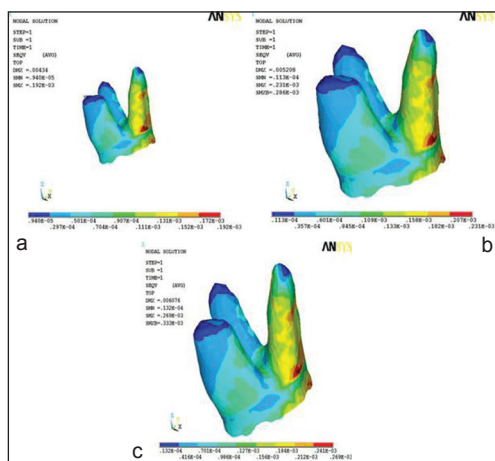

Figure 11: von-mises stress contours in periodontal ligament (a) at 150 g force (b) at 180 g force (c) at 210 g force
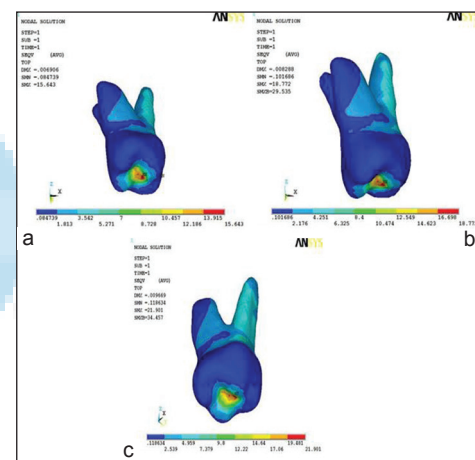

Figure 12: Von-mises stress in tooth (a) at 150 g force (b) at 180 g force (c) at 210 g force
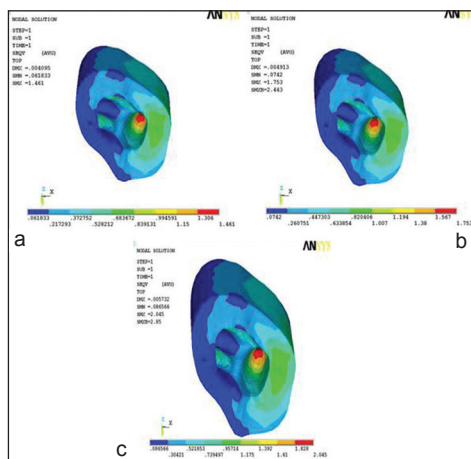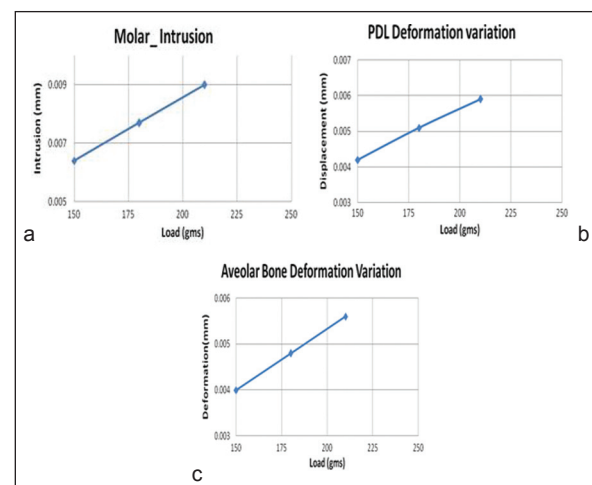

Figure 13: Von-mises stress in alveolar bone (a) at 150 g force (b) at 180 g force (c) at 210 g

Graph 1: Displacement in Z-axis (vertical) at 150 g, 180 g and 210 g of load in (a) tooth; (b) periodontal ligament and (c) alveolar bone

complete root area except at the palatal side of palatal root where stretching was observed to take place due to tensile forces. Tooth compression was observed at the majority of tooth area except at the central fossa region where tensile forces were seen. At the alveolar bone region, compression was observed at all places except in the apical region covering the palatal root where tensile forces were present.

When quantifying the maximum principal stress in PDL, compression was seen in the whole area of PDL except in furcation area where stretching was seen due to tensile forces. For the tooth, compression was seen in the area of central fossa while in alveolar bone compression resulted in the apical area of bone covering palatal root [Graph 2a-c].

The results were similar to that of Jeon *et al*.[13] who observed high stress concentration on the root surface at furcation level, was in contrast to anterior teeth that display a greater apical concentration.[14-17] In a recent clinical study[15] maxillary central incisors showed the highest incidence (over 60%) of apical resorption as a result of orthodontic treatment while maxillary molar showed the least. The maxillary molar with three roots was likely to undergo resoption on the root surface at furcation level that was difficult to infer radiographically.

The viscous nature of PDL comes from the cervicular fluid and its elastic behavior from the PDL fibers. The anisotropy resulted from the orientation of fibers. Studies have been done to examine anisotropy[18] and viscoelastic behavior[19] of PDL which is characterized by time-dependent strain[20] but have been limited to 2-D analysis.

In the present study, static FEA only simulated the initial tooth movement in periodontal membrane and the

initial stress distribution along the root surface. During the treatment cycle, ongoing movements and stresses could differ due to changes in force systems and biologic responses. Other limitations were:

1. Use of physical properties of the tissues, which would normally alter clinically through the histologic process and
2. The assumptions that periodontal membrane as homogenous, isotropic and uniform thickness.

These limitations could cause differences between clinical and simulation studies. However, similarities between the results of the present study and the clinical studies with parallel mechanics have shown that finite element models generated are accurate enough to simulate clinical conditions, in accordance with Yao *et al*.[21] and Ammar *et al*.[22]
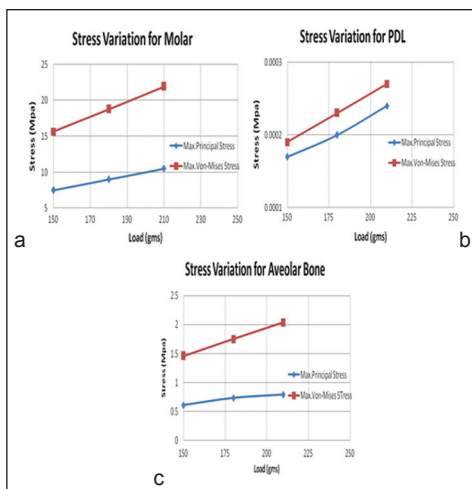
Conclusion

Resorption during intrusion is one of the factors among various tooth movements which is considered to be detrimental. It is well established that the intrusive forces generate stress which cause changes in the surrounding tooth structure and its periodontium.

1. In the present study, a high stresses concentration on the root surface area at the furcation level was observed, which was in contrast to anterior teeth that display a greater apical concentration; these areas were, therefore, prone to resorption.
2. Heavy forces tend to produce more orthodontically induced inflammatory resorption when compared with light forces. Comprehensive orthodontic treatment causes increased incidence and severity of root resorption especially when treatment is carried over a prolonged period of time.
3. In order to obtain a balanced intrusion, root surface area should be considered when determining the appropriate forces. Over the years FEA have been used as a tool for simulating various orthodontic movements and stress patterns.
4. FEA of maxillary 1st molar intrusion only simulates the initial tooth movement in periodontal membrane and the initial stress distribution along the root surface.
5. Similarities between the results of the maxillary molar intrusion and the clinical studies with parallel mechanics shows that finite element models generated are accurate enough to simulate clinical conditions.
6. Ideally, the results gained through FEA should be integrated with clinical experiences to maximize accuracy.

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Graph 2: Stress generation at different loads 150 g, 180 g, 210 g in (a) tooth (b) periodontal ligament and (c) alveolar bone

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